Integration of renewables in large-scale hydrogen production

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European grid operators (ENTSO-E) expects large-scale RES integration

- Variable RES will dominate generation
- Ca 100 000 MW offshore wind in the North Sea

Figure: ENTSO-E TYNDP
The merit-order effect reduces price

- Variable renewables have zero marginal cost
  - Periods with zero (or negative) prices become more common
Why flexibility matters

![Wind power production graph]

- **90 GW**
- **15 GW**
- **15 hours**

Figure: T. Aigner, Phd thesis, NTNU, 2013
H2 production from renewables in Northern Europe

• Nordic power surplus will increase significantly
• Huge onshore and offshore wind potential in Norway
  – Many projects on wait due to low prices and/or low grid capacity
• The hydrogen path is a promising alternative for utilization of the vast renewable energy potential
  – Especially in the North
• Methods for the design, sizing and operation strategy of the electrolysis path must be developed
  – Using surplus wind/hydro for hydrogen..
  – or producing hydrogen as the main operating strategy?
  – Optimal integration in the whole LH2 production and export chain
Model of regional power system with wind, hydro and hydrogen production

• Centralized optimization
  – Maximize profit from power exchange
  – Minimize investment cost
  – One year horizon, hourly time stages

• Storage balance
  – Hydropower and hydrogen storage
  – Hydrogen demand given as input

• Energy balance

• Realistic grid model

• Plant modelling
  – Power plant capacities, electrolyser and storages
Case Study: Northern Norway

- Finnmark in northern Norway
- Existing LNG facility
- Suitable site for H2 prod from NG
- Very good wind potential
- Some existing hydro power
- Weak transmission grid
- Liquification alone requires significant electric power
- Electrolyser options
  - Maximize electrolyzer utilization (and minimizing need for hydrogen storage)
  - OR Install overcapacity in electrolyser and hydrogen storage (Increase flexibility)
Flexible or continuous H2 production in constrained power grids?

- Even flexible H2 production leads to high degree of H2 storage utilization and requires additional electrolysers
  - From 108 MW to 130 MW capacity for 10 hour storage
- Flexibility is important to increase power system security due to the new demand from the H2 system
- Flexibility helps integrate more wind power without high levels of curtailment
- A strong grid favors continuous H2 production
Wind power uncertainty

• In the previous analysis, wind power variability was treated as known with 100% accuracy
  – This is a normal assumption in cost-benefit analyses of energy systems
  – Do not capture the imbalance cost of wind in the market
• How important is it to include wind power uncertainty in the models?
  – How does it affect hydrogen storage strategies?
  – Does it change the optimal hydrogen system investments?
Operational model of H2 production including balancing cost for wind
Impacts of wind power uncertainty

• A high imbalance penalty was set to test the model
• Case study shows:
  – Uncertainty model reduced costs by 5.6% compared to standard model
  – Perfect forecast reduced costs by 37.6%
  – Robust approach: Similar solutions for 60 different wind samples

  – Same main conclusion as before: Flexible H2 production increases the supply security in constrained grids.
Utilizing hydropower flexibility for H2-production
More hydro flexibility gives more stable H2 production
Flexible hydro production reduces H2 costs in constrained grids

- DOE 2015
- DOE 2020
- Our system (low)
- Our system (hi)

Feedstock cost [€/kg] vs. Hours of Hydro Power Flexibility [h]
Conclusions

• H2 production and liquefaction increases the optimal amount in wind power in constrained grids
• Power consumption of liquifier can be challenging from a grid perspective
• It is optimal to «oversize» the electrolyzer+H2storage to operate in a flexible manner
  – Reveal grid constraints, utilize more wind, reduce wind imbalance costs
• Flexible hydropower in North of Norway can be utilized to bring H2 production costs further down
• Current work: Capture the value of H2 flexibility (production and storage) in H2 plant investment model
Extras
Hyper and the power grid: Published and accepted publications


Hyper and the power grid: Papers in progress

• E. F. Bødal, D. , A. Botterud, D. Mallapragada, M. Korpås. **Towards Large Scale Hydrogen Production: Centralized versus Local Production.** In preparation for Applied Energy
  – Cooperation with MIT
  – Using case study from Texas
  – Supervision of master student: Case for North-Western Europe

• E. F. Bødal, Audun Botterud, M. Korpås. **Representing Short-Term Uncertainties in Capacity Expansion Planning Using an Rolling-Horizon Operation Model.** In preparation for IEEE Transactions on Power Systems
  – Cooperation with MIT
  – Generalised investment model for any combination of renewables and storage
  – Future work: Apply model to the wind-hydrogen Finnmark case
Operational model based on stochastic optimization